A Multi-Disciplinary Mechatronics Laboratory

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Abstract: The global engineering market requires engineers who embrace a mechatronics perspective with critical systems skills for participation on multi-disciplinary teams. Mechatronic systems focus on the harmonious integration of electronics, sensors, actuators, and digital technology into dynamic systems. In this paper, a series of mechatronic laboratory experiments are presented for hardware and software skill achievement. The electronic circuit exercises introduce signal conditioning concepts, as well as the selection of semiconductor components. Programmable logic controller (PLC) algorithms are created using ladder logic on Allen Bradley equipment. A National Instruments multiple input/output board and LabView software regulate the operation of pneumatic and hydraulic cylinders, as well as the dc servo-motor with electric brake for performance studies.

1. Introduction

The twenty-first century engineer must be proficient at working on multi-disciplinary engineering teams for manufacturing, consumer, and defense products. The integration of electrical, mechanical, chemical, aeronautical, and marine systems with assorted sensors, actuators, and embedded microprocessors requires a holistic (mechatronics) engineering strategy to yield products with greater functionality, reliability, and compatibility. The prevalence of mechatronic systems is becoming widespread throughout society as evident by the transportation, consumer products, health care, and manufacturing sectors [1,2] shown in Figure 1. Today's engineering graduates require a mechatronics background in addition to the engineering fundamentals, communication skills, and leadership qualities necessary to successfully compete and prosper in the global market.

The introduction of mechatronics concepts [3] in the industrial workplace allows manufacturers enhanced flexibility in the customization and/or diversity of their products. For instance, the routing of specific items between various reconfigurable manufacturing cells requires intelligent conveyor systems with a multitude of sensors to identify and sort parts without operator intervention. Similarly, the successful fusion of sensor data, with control algorithms for servo-motor actuation, requires a team approach for conceptualization, implementation, and support to realize speed and quality goals. Finally, the transportation industry is developing advanced engine, transmission, chassis, and safety systems to provide increased vehicle performance, fuel economy, passenger safety, and comfort. In each instance, a mechatronics background facilitates the

individual's contributions to the team's efforts. Thus, a critical need exists to provide engineering graduates with mechatronics concepts (lecture) and "hands on" skills (focused laboratory experiments).

Figure 1. Overview of representative mechatronic sectors and associated products

A key strength of the mechatronics course is the laboratory which encourages students to apply, and absorb, mechatronic concepts [4]. The Rockwell Automation Mechatronics Laboratory, in the Department of Mechanical Engineering at Clemson University, complements the classroom lectures through a sequence of electrical, mechanical, pneumatic, and hydraulic experiments [5]. These multi-disciplinary systems feature the integration of sensors, actuators, and real time data acquisition and controls using industrial hardware/software. Student teams have an opportunity to i) develop mathematical models for the dynamic plants, ii) apply basic control theory concepts, iii) analyze the system behavior for both open-loop and closed-loop performance, iv) gain insight into the operation of assorted sensors and actuators, and v) develop problem solving strategies. In addition, the team approach for the laboratories facilitates the students' refinement of their interpersonal and technical communication skills. In general, the laboratory tasks may be divided into four units: electrical and electronic fundamentals, programmable logic controller experiments, personal computer workstation controllers, and dc motor systems.

2. Electronic Circuit Experiments

The first series of experiments focus on electrical/electronic fundamentals that may have been introduced in previous engineering courses. However, some graduate students may have completed these classes at their undergraduate institutions. Overall, students welcome the opportunity to explore passive, semiconductor, and digital components and technologies. The focus of the exercises may be readily adjusted to reflect questions and/or discussions from the classroom to further emphasize key concepts. For this paper, two assignments will be discussed: photo-electric sensor with attached filter, and digital-to-analog converter (DAC).

The learning objectives for these laboratory exercises include:

- Understanding the operation of operational amplifiers, LEDs, and photo-resistor devices
- Developing an ability to design and analyze electrical circuits

- Assembling components on a breadboard; probe test points using bench tools to validate circuit
- Designing analog filters through the selection of resistor-capacitor combinations
- Recognizing the need to prevent over-voltage circuit damage; designing of zener diode solutions

The first laboratory exercise is the creation of a light sensitive circuit with an attached analog filter. Student teams design, analyze, and test a circuit in which an LED illuminates (turns off) when the surroundings are variably dimmed (fully lit) similar to a night light. A photo-resistor, whose resistance is proportional to the intensity of visible light absorbed, is the key component (refer to Figure 2). Specifically, the cadmium sulphide device (CDS004) provides low resistance when exposed to large amounts of light, and high resistance when immersed in darkness. An analog comparator (LM741) is attached to compare the photo-resistor's output and user-defined potentiometer-based voltages. The LED requires a current limiting resistor.

Figure 2. Electrical schematic diagram for light sensitive and analog filter circuit (solid: original circuit, dashed: analog filter; dashed-dot: circuit protection)

Next, an adjustable time delay shall be introduced into the system using a resistor-capacitor (RC) analog filter across the operational amplifier (op-amp). The RC network allows various filter behaviors to be studied by adjusting the resistor and capacitor values to effect the system response. Finally, a zener diode, with any other necessary components, is added to protect the LED from large output voltages when the op-amp saturates. For circuit protection, zener diodes may be added to maintain the circuit voltage below the zener diode breakdown voltage. The basic skills to acquire include circuit design and analysis, bread boarding, and application of bench top tools (e.g., handheld multimeter, oscilloscope) to validate the circuit.

In the second experiment, a digital-to-analog conversion process is explored. DACs allow digital systems to interface with analog circuits and devices using a user-selected number of bits for appropriate resolution. Student teams are assigned tasks to design, build, and test a circuit that converts an 8-bit digital signal into an equivalent analog voltage to drive a small dc servo-motor (refer to Figure 3). The components available to the teams include an 8-bit AD558 DAC chip, DIP switch bank, assorted resistors, and LEDs. The digital input consists of the DIP switch bank, connected to either 5VDC or ground, to generate various digital "words" for conversion into analog voltages. For visual feedback, each bit is connected to an LED. To limit the current for

safe LED operation, 330Ω resistors are inserted between the switches and each LED. The 8-bit DAC provides a 0-10V output voltage for a 11.4-16.5VDC supply voltage. Resistors may also be placed between the switch bank and the DAC to prevent the input signals from "floating" when unpowered. The DAC chip output should reflect that a 1-bit digital input converts into approximately 0.039V output. Finally, a voltage/current power amplifier subsystem (e.g., PA73 and LM324) is inserted after the DAC chip to drive a small electric motor. Students should use various digital input signals combinations to explore system operation.

Figure 3. Digital-to-analog converter circuit with motor load

3. Programmable Logic and National Instruments Control Systems

The programmable logic controller (PLC) and National Instruments experiments introduce students to ladder logic programming, control architectures, Allen-Bradley PLCs, and LabView software. The learning objectives, laboratory equipment, and student tasks have been presented in Ghone *et al.* [5]; however, a brief overview will be provided in this paper. In the laboratory, PCs host Allen-Bradley RSLogix™ SLC500 PLC software which is interfaced to Allen-Bradley MicroLogix 1000 micro-controller with 16-bit precision and 1K-user memory capacity. Direct PC to PLC connectivity is achieved through an RS-232 port. The MicroLogix has a comprehensive instruction set with 12 basic logic instructions, 43 applied control instructions, and 14 advanced application-specific instructions. Execution for a typical 500-instruction program is 1.56 ms. The RSLogix software permits ladder logic programming (Figure 4) to regulate the PLC. Ladder diagrams provide a graphical representation of the algorithm using two vertical lines attached by horizontal lines, called rungs, which contain the logical operators. The project tree and ladder windows facilitate the creation, editing, monitoring, and troubleshooting of programs. The project tree provides configuration, program, and data file access. The logical operators may be accessed through the "Instruction Toolbar" with drag and drop capability into the ladder window. Data elements include 512 bits, 40 timers, 32 counters, 16 control files, 105 integer files, and 33 diagnostic states with more than 735 words. Note that some PLCs may be programmed in function block diagrams, instruction lists, and C/C++.

The laboratory allows students to compare the programming capabilities and applicability of PC-based National Instruments hardware/software for controlling mechatronic systems. The hardware

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selected is a multiple I/O board (PCI-6025E) with 16 analog inputs (12-bit resolution), 2 analog outputs (12-bit resolution), 32 digital lines, and 2 24-bit counters. The LabView™ software package provides a user reconfigurable computer interface for instrument control, data acquisition, analysis, storage, and presentation using "virtual instruments" (VI). A virtual instrument is comprised of three main parts: the front panel, the block diagram, and the icon/connector panel. The front panel receives (displays) the input (output) values, which are termed "controls" ("indicators"). Simply put, the VI is analogous to an instrument's front panel with a variety of graphical user interface (GUI) features (e.g., knobs, switches, buttons, graphs). The control loops (i.e., VI wiring diagrams) are written in the block diagrams as virtual machine interfaces. Several control loops in the standard VI library are incorporated to facilitate large-scale system integration. LabView contains software drivers to communicate with I/O boards.

Figure 4. RSLogix 500 software diagram for light stack experiment

A variety of experiments exist for data acquisition and control using PLCs and National Instruments in the mechatronics laboratory. Students begin with a "traffic light" sequencing experiment (i.e., on/off electrical switching) to investigate PLCs, wiring diagrams, and Allen-Bradley software programming (refer to Figure 5). Next, a pneumatic cylinder, pneumatic solenoid valve, and proximity sensors introduce analog-to-digital (ADC), digital-to-analog (DAC), and digital input/output concepts with accompanying LabView software input/output routines. Third, the student teams work with a PLC controlled scaled drag chain conveyor system (single phase motors) with assorted proximity and optical sensors, and a pneumatic actuator for part transport and removal. Finally, hydraulic components and concepts are explored using a hydraulic cylinder, motor, and valve, as well as assorted sensors (e.g., LVDT, optical encoder,

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pressure) interfaced with PLC control algorithms. The reader is referred to [5] for information.

4. DC Motor Experiment

Electric motors, which convert electrical energy into rotational motion, range in design (dc: permanent magnet, series wound, shunt wound; ac: single phase induction, synchronous) and size based on the application. A motor contains a rotor (i.e., metal shaft with slats with longitudinally wrapped wire) and a stator (i.e., stationary metal cylinder which contains permanent magnets or wire coils to produce a radial magnetic field). An electric current produces a magnetic field which exerts a force on the armature causing a net torque. An understanding of a motor's physical design, dynamic behavior, control architecture, system integration, and performance (e.g., torque versus speed) is a key goal. Although motors may have been previously discussed in other courses, the "hands on" servo-motor experiment allows students to explore a commercial grade controller operated with National Instruments hardware and LabView software. Specifically, the LabView program can perform data acquisition and the generation of plots via logged motor controller output data. The motor load will be applied by an electric brake; the motor's speed will be measured using factory mounted tachometers which permit feedback to the motor controller for closed-loop operation.

Figure 5. Schematic wiring diagram for PLC light stack experiment

The learning objectives for this laboratory exercise include:

- Gaining insight into the different types of electric motors and their performance characteristics
- Understanding the functionality and architecture of a commercial grade motor controller
- Designing and introducing an electric brake to regulate the motor shaft's motion
- Applying National Instruments hardware/software to perform data acquisition and control

An overview of the major dc motor configurations is briefly presented. Permanent magnet motors create the magnetic field with permanently magnetized metal, thus eliminating the energy required for the field windings. However, the magnetic field cannot be adjusted per the loading; the available torque decreases as the motor speed increases. Series wound motors contain the field windings in series with the armature coil windings (i.e., uniform current) and provide excellent starting torque. A shunt wound motor features the field coil in parallel with the armature windings (i.e., uniform applied voltage); it delivers smaller starting torques and excellent high speed characteristics. Finally, a compound wound motor provides two fields (i.e., shunt wound and series) to offer the benefits of the shunt and series motors.

A Reliance Electric permanent magnet (part no. T56S2005, 1/2 horsepower, 1750 rpm, totally enclosed fan) motor with factory mounted tachometer (part no. RE-007) was chosen based on its overall robustness and safety. An open-plate DC motor controller (part no. DC2-54U, 115VAC) was selected since the open-plate design allows students to view the electronic components and alter potentiometer/jumper settings. The load cell transducer (Sensotec, part no. AL311AR) and electric brake (Dodge PT Engineering, part no. 31351) were added to the motor shaft to permit varying loads and lever arm torque measurements. The DC controller and associated instrumentation can export electronic data directly to the PC hosting the National Instruments I/O board and executing LabView. This LabView file performs basic communication with the motor controller, calibration of the incoming data, control of the sample rate, real time plotting of the data, and data storage. A system schematic is shown in Figure 6.

Figure 6. DC motor experimental system configuration - wiring and signal routing

In this experiment, the student team first edits the LabView algorithm by reviewing the input/output protocol, initial motor control set points, data acquisition, and display functions.

Second, the motor controller's wiring is reviewed (e.g., sensory inputs, motor output, and National Instruments I/O board lines) as well as its internal control architecture. Third, the electric brake and load cell are checked to ensure proper integration in the shaft and calibration. Finally, testing is ready to commence with control in both a "manual" (open loop) and an "automatic" (closed loop) mode based on the setting provided to the controller by the control software. Students should adjust the electric brake and observe the motor speed changes. A series of real time plots of the torque versus speed may be displayed and discussed.

5. Summary

The Rockwell Automation Mechatronics Laboratory offers a variety of experimental systems for students to explore classroom theory and gain insight into engineering concepts. The laboratory exercises are framed so that instrumentation, sensor/actuator integration, alternative control architectures, and safety issues may be addressed. Several electrical/electronic circuit designs are initially assigned to introduce signal processing concepts and semiconductor component selection. PLCs are then explored (providing familiarization with typical industrial automation hardware) to regulate the operation of light stacks and conveyor belt systems. Next, personal computer workstation controllers with pneumatic and hydraulic systems are controlled using LabView. Finally, a dc servo-motor system is controlled using LabView to investigate motor performance issues.

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References

1. Hargrove, J. B., "Curriculum, Equipment and Student Project Outcomes for Mechatronics Education in the Core Mechanical Engineering Program at Kettering University", *Mechatronics*, vol. 12, no. 2, pp. 343-356, February 2002.
2. Hsu, T., "Undergraduate Curriculum Development in Mechatronic Systems Engineering", proceedings of the ABET Annual Meeting, San Diego, CA, pp. 140-147, 1996.
3. Auslander, D., "What is Mechatronics", *IEEE Transactions on Mechatronics*, vol. 1, no. 1, 1996.
4. Ume, I. C., Kita, A., Liu, S., and Skinner, S., "Graduate Mechatronics Course in the School of Mechanical Engineering at Georgia Tech", *Mechatronics*, vol. 12, no. 2, pp. 323-335, February 2002.
5. Wagner, J., "Evolving Ghone, M., Schubert, M., and Wagner, J., "Development of a Mechatronics Laboratory - Eliminating Barriers to Manufacturing Instrumentation and Control", *IEEE Journal on Industrial Electronics*, vol. 50, no. 2, April 2003.